Technical Report

Third Quarterly Progress Report: Development of an HY-130/150 Weldment

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THIRD QUARTERLY PROGRESS REPORT: DEVELOPMENT OF AN HY-130/150 WELDMENT
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Abstract

During the period January 1 to March 31, 1964, work has continued on Bureau of Ships Contract No. NObs-88540, SR007-01-01, Task 853, to develop a submarine-hull weldment with a yield strength in the range 130 to 150 ksi (HY-130/150). The present report summarizes the results obtained during that period and describes the activities that are currently in progress and the activities that are planned for the immediate future.

A detailed evaluation of the base-metal properties of the 80-ton production heat of the 5Ni-Cr-Mo-V steel confirmed previous observations that this steel is most promising as an HY-130/150 steel and indicates that it can be produced on conventional commercial facilities as 1/2- through 4-inch-thick plates that exhibit good uniformity of properties. Programs are now in progress to evaluate the effect of deoxidation practice, the effect of small variations in C, ~~Mn,~~ Cr, and Mo, and the effect of stress relieving on the properties of the 5Ni-Cr-Mo-V steel; programs are being initiated to determine the effect of melting and processing variables on the properties and to determine the forgeability and castability of the 5Ni-Cr-Mo-V steel.

The study of the composition limits within which minimum crack susceptibility and maximum notch toughness are obtained in the heat-affected zone of Ni-Cr-Mo steels has been completed, and the results have been used in the selection of composition limits for the 5Ni-Cr-Mo-V steel. Preliminary explosion-bulge tests of 5Ni-Cr-Mo-V steel weldments showed that experimental HY-130/150 weldments can be fabricated that will undergo extensive plastic flow during explosive loading without fracture. Future joining-development studies will emphasize the development of all-position techniques for the MIG process, improvement in the toughness of weld metals deposited from covered electrodes, and an evaluation of the weldability of heavy, highly restrained weldments.

The program to evaluate the structural suitability of the 5Ni-Cr-Mo-V steel has been initiated in the areas of strength and formability, fatigue, fracture, weldability, and corrosion. Drop-weight tear tests indicate that the energy absorption of the conventionally processed 5Ni-Cr-Mo-V steel is equal to that of the best specially processed high-yield-strength steels tested to date by the Naval Research Laboratory.

The results obtained to date indicate that a steel and compatible filler metal meeting most of the requirements for an HY-130/150 weldment are ~~now~~ available. Th~~erefore,~~ emphasis can now be placed on adapting the weldment to the requirements of shipyard submarine-hull fabrication. ( )

INTRODUCTION

During the period January 1 to March 31, 1964, work has continued on Bureau of Ships Contract No. NObs-88540, SR-007-01-01, Task 853, to develop a submarine-hull weldment with a yield strength in the range 130 to 150 ksi (HY-130/150). The status of the program as of December 31, 1963, including work in progress, was summarized in the second quarterly report.[1)*] Most of the studies that were in progress at that time have been completed or significantly advanced during the third quarter. The detailed results of these studies have been described in seven individual reports, which are summarized in the present report. In addition, the present report describes the activities that are currently in progress or planned for the immediate future to develop an HY-130/150 weldment.

BASE-METAL DEVELOPMENT

During the past quarter, studies have been completed and reported on (1) an evaluation of 3Ni-Cr-Mo steels and (2) a detailed evaluation of a production electric-furnace heat of the experimental HY-130/150 5Ni-Cr-Mo-V steel. Work has been completed and reports are being prepared on (1) the effect of strong nitride formers and deoxidizers and (2) an evaluation of Ni-Cr-Mo steels with high M_s temperatures; experimental work is nearing completion on (1) the effect of carbon content on the properties of 5Ni-Cr-Mo-V steel, (2) the effect of stress-relieving treatments on the

* See References.

mechanical properties of 5Ni-Cr-Mo-V and HY-80 steels, and (3) the effects of variations in minor elements (Si and Al) and minor variation in major elements (C, Mn, Cr, and Mo) on the properties of the 5Ni-Cr-Mo-V steel.

In addition, because the 5Ni-Cr-Mo-V steel continues to look promising, programs have been initiated to determine the effects of variations in cross-rolling ratios on the properties of the 5Ni-Cr-Mo-V steel and to obtain additional production experience by melting a second 80-ton electric-furnace heat of the steel. The plate product of this heat will be extensively evaluated in welding and structural-evaluation studies.

Detailed plans have been completed and work has been scheduled to determine the effect of steelmaking practice—oxygen steelmaking (OSM), vacuum-carbon deoxidation (VCD), and vacuum-consumable-electrode remelting (VCE)—on the properties of the 5Ni-Cr-Mo-V steel. Sample forgings and castings of this steel will be produced and evaluated.

Work Completed

Evaluation of 3Ni-Cr-Mo Steels[2)]

Previous investigations indicated that a 3Ni-Cr-Mo steel having improved hardenability and temperability would be promising as an HY-130/150 steel. Therefore, the Applied Research Laboratory investigated the extent to which additions of nickel, vanadium, columbium, and/or tantalum would improve the hardenability, temperability, and mechanical properties of four 0.25 percent carbon and four 0.15 percent carbon 3Ni-Cr-Mo steels.

The results summarized in Figure 1 show that the 0.25 percent carbon steels had just sufficient hardenability for 4-inch-thick water-quenched plates, but that the 0.15 percent carbon steels did not have sufficient hardenability. The addition of vanadium, columbium, and/or tantalum increased the resistance of the 0.25 and the 0.15 percent carbon steels to softening during tempering. These additions generally reduced the Charpy V-notch energy absorption of the 0.25 percent carbon steels but did not reduce the energy absorption of the 0.15 percent carbon steels that were cooled rapidly enough so that they hardened fully.

Among the steels investigated, an 0.25 percent carbon, low-manganese (0.13%), low-silicon (0.05%) 3Ni-1.5Cr-0.9Mo steel exhibited the best combination of strength and toughness over the yield-strength range 120 to 210 ksi, and appears promising as an HY-130/150 or an HY-180/210 steel. However, this steel has distinctly poorer tempering characteristics and weldability than the 5Ni-Cr-Mo-V steel that has been extensively evaluated as an HY-130/150 steel. Therefore, further work to develop 3Ni-Cr-Mo steels as HY-130/150 steels will be discontinued; however, work to establish the potential of 0.25 percent carbon 3Ni-Cr-Mo steels as HY-180/210 steels will be continued.

Evaluation of a Production Electric-Furnace Heat of 5Ni-Cr-Mo-V Steel[3)]

A preliminary evaluation of an 0.10 percent carbon 5Ni-0.5Cr-0.5Mo-0.07V steel indicated that the steel was very promising as an HY-130/150 base

metal. Therefore, 1/2-, 1-, 2-, and 4-inch-thick plates from an 80-ton electric-furnace heat of the 5Ni-Cr-Mo-V steel were more completely evaluated to determine their uniformity of mechanical properties and the effect of various austenitizing and tempering treatments on the mechanical properties.

The heat-treating studies showed that (1) the tempering characteristics of the production plates were similar to those of the Laboratory 5Ni-Cr-Mo-V steel, (2) blower cooling 1/2-inch-thick plates to simulate the cooling at the midthickness of a 4-inch-thick water-quenched plate was a conservative simulation as previously reported, (3) the 5Ni-Cr-Mo-V steel has adequate hardenability for 4-inch-thick plates, and (4) the tensile and impact properties of heavy-gage 5Ni-Cr-Mo-V steel plates are slightly improved by a double- versus a single-austenitizing treatment.

The studies of the uniformity of the production plates showed that the longitudinal and transverse tensile and impact properties of the 1/2- through 4-inch-thick production plates of the 5Ni-Cr-Mo-V steel were generally uniform. The only significant trend was a small decrease in strength and notch toughness as the plate thickness increased.

The results confirm previous observations that the 5Ni-Cr-Mo-V steel is most promising as an HY-130/150 steel and that it can be produced on conventional commercial facilities as 1/2- through 4-inch-thick plates that exhibit a very attractive combination of strength and toughness and generally good uniformity of properties.

Work in Progress

Effects of Strong Nitride Formers and Deoxidizers

As discussed in the second quarterly report,[1)] this study has been completed. However, because of low priority the final report is still in process.

Development of a Ni-Cr-Mo Steel with a High M_s Temperature

This study was summarized in the second quarterly report.[1)] The final report of the results has been drafted and is now being edited.

Effect of Carbon Content on the Properties of 5Ni-Cr-Mo-V Steel

The preliminary results of this study were discussed in the second quarterly report.[1)] All the data are now available and a more complete summary of the results is shown in Table I. As indicated previously, when the 5Ni-Cr-Mo-V steel contained 0.05 percent carbon, blower-cooled 1/2-inch-thick plates exhibited a maximum yield strength of only 110 ksi and a microstructure consisting of at least 50 percent bainite. At about 0.15 percent carbon or above, the blower-cooled 1/2-inch-thick plates exhibited a microstructure of 100 percent martensite. Although increasing the carbon content of the 5Ni-Cr-Mo-V steel increased the yield strength and decreased the notch toughness, the degree of impairment to toughness was not severe. For example, the 0.22 percent carbon steel exhibited yield strengths in the range 156 to 163 ksi and energy-absorptions at 0 F in the range 55 to 75 ft-lb. A yield strength of 180 ksi could not be obtained in any of the

steels at tempering temperatures of 900 F or higher, even when the carbon content was increased to 0.26 percent.

Effect of Stress-Relieving Treatments on the Mechanical Properties of 5Ni-Cr-Mo-V and HY-80 Steels

Because stress relieving after welding, if required, or sub-critical heating prior to or during forming, if required, may significantly alter the mechanical properties of the 5Ni-Cr-Mo-V base metal, a study was initiated to determine the effects of stress relieving (at temperatures in the range 950 to 1050 F for times up to 125 hours) on the mechanical properties of water-quenched and blower-cooled 1/2-inch-thick plates produced from an electric-furnace heat of 5Ni-Cr-Mo-V steel. For comparison, a similar study was conducted on 1/2-inch-thick plates of an open-hearth and an electric-furnace HY-80 steel. Although all the data are not yet available, it appears that the toughness of all the steels is lowered slightly by stress relieving for times up to 25 hours.

Effect of Minor Elements and Minor Variations in Major Elements on the Properties of 5Ni-Cr-Mo-V Steel

This study was designed to help establish the specification ranges for production melting of the 5Ni-Cr-Mo-V steel and to determine whether any improvements or impairments in hardenability, toughness, etc., occur as a result of minor variations in composition. The minor elements (silicon and aluminum) and the major elements (carbon, manganese, chromium, and molybdenum) are being studied by examining the steel compositions shown in

Table II. Initial results on Steels A, B, and H were discussed in the second quarterly report.[1] Mechanical tests on the other five steels have not been completed.

It is anticipated that this study will be followed by a statistically designed experiment to determine whether a leaner, more economical alloy should be specified for heats being produced for light-gage plates than the alloy that would be specified for heats being produced for heavy-gage plates.

Work Planned

Effect of Production Processing Procedures on the Properties of 5Ni-Cr-Mo-V Steel

A study of the effect of straightaway rolling and of cross-rolling ratios of 16 to 1, 8 to 1, 4 to 1, and 1.6 to 1 on the properties of 5Ni-Cr-Mo-V steel has been initiated. Sections from a 7-1/4-inch-thick slab (from heat No. X53185) will be hot-rolled on the Laboratory mill to 1-inch-thick plates with each of the above rolling ratios. The rolling will be carefully controlled to ensure that the slabs are all heated in the same manner and finished at the same temperature and with the same reduction during the final passes through the rolling mill. The plates will all be air-cooled in the same manner after rolling. Longitudinal and transverse tensile and impact properties will be determined on the rolled plates before and after heat treatment (quenching and tempering).

roduction of Second Electric-Furnace Heat of 5Ni-Cr-Mo-V Steel

A second 80-ton electric-furnace heat of the 5Ni-Cr-Mo-V steel has een scheduled for the month of April. The chemical composition of this eat will be adjusted so that the major elements (C, Mn, Ni, Cr, and Mo) are n the high side of the range specified for the initial heat. This heat will e used to provide plate material for continuing evaluation by cognizant avy laboratories, and for extensive welding and structural-evaluation udies at the Applied Research Laboratory and the Air Reduction Company. e adjusted chemical compositions will permit an evaluation of the effects f a high-side composition on the properties of 1/2- through 4-inch-thick lates of this steel.

fect of Steelmaking Practice on the Properties of 5Ni-Cr-Mo-V Steel

Plans have been completed to produce a 40-ton heat of the i-Cr-Mo-V steel by the oxygen steelmaking process (OSM). The heat will be de to the same chemical composition limits and aim as the initial electric-rnace heat. A second 40-ton OSM heat will be further refined by ladle-to-dle vacuum-carbon deoxidation (VCD). A 32- by 57-inch slab ingot will be st from each heat. In addition, a 28-inch-diameter ingot will be cast om the standard OSM heat, and a 25- by 25-inch ingot will be cast from e VCD heat. The slab ingots will be converted to plate product (1/2-, , 2-, and 4-inch-thick plates); the 28-inch-diameter ingot will be cuum-consumable-electrode remelted (VCE); and the 25-inch-square ingot

will be reserved for forging studies. Material from each of these ingots will be heat-treated and evaluated.

Forging and Casting Studies

The forging characteristics of the 5Ni-Cr-Mo-V steel will be evaluated by producing 30-inch-diameter by 28-inch-high ring forgings with 6-inch-thick walls. Material for these forgings will be obtained from the 25- by 25-inch ingot from the vacuum-carbon-deoxidized OSM heat.

Initial studies of the casting characteristics of the 5Ni-Cr-Mo-V steel will be conducted by casting 1- by 6- by 6-inch and 3- by 12- by 12-inch test coupons from air-induction-melted heats. Core boxes are now being prepared for this study.

JOINING DEVELOPMENT

During the past quarter, work has been completed on (1) the toughness and transformation characteristics of the weld-heat-affected zones in Ni-Cr-Mo steels, (2) the effects of composition on the properties of covered-electrode weld metals, (3) a weld-metal cooling-rate study, and (4) preliminary explosion-bulge tests. In addition, work is continuing on (1) several base-metal weldability studies, (2) a parametric study of out-of-position MIG welding, (3) a MIG major-element study, and (4) a second series of explosion-bulge tests.

Work Completed

Base-Metal Weldability

Effects of Composition on the Transformation Characteristics and Toughness of Weld-Heat-Affected Zones in Ni-Cr-Mo Steels. As part of the program to define the composition limits within which an HY-130/150 steel would exhibit satisfactory weldability, the effects of carbon (0.05 to 0.21%), manganese (0.3 to 1.5%), phosphorus (0.003 to 0.027%), sulfur (0.003 to 0.027%), and nickel (1.0 to 9.0%) on the crack susceptibility, transformation characteristics, and toughness of the weld-heat-affected zone were determined on 32 statistically selected Ni-Cr-Mo steels. The results of the previously reported[4)] crack-susceptibility study indicated that an increase in carbon, particularly at high nickel contents, strongly increased crack susceptibility, that an increase in manganese content increased crack susceptibility less strongly, and that an increase in nickel at high carbon contents moderately increased crack susceptibility. Phosphorus and sulfur did not significantly influence crack susceptibility.

The transformation and toughness studies have recently been completed[5)] and the results have been analyzed statistically. The results of the transformation study showed that changes in the martensite-start (M_s) temperature depended primarily on the carbon, manganese, and nickel contents, that the M_s temperature varied inversely with the carbon, manganese, and nickel content, and that the crack susceptibility of the

weld-heat-affected zones varied inversely with the M_s temperatures. These results support the theory that stresses set up during transformation of the weld-heat-affected zone to martensite are the primary cause of cracking in Ni-Cr-Mo steels, and that an increase in the temperature range of martensite formation would reduce transformation stresses and therefore reduce crack susceptibility.

The results of the toughness study showed that an increase in the sulfur content of Ni-Cr-Mo steels strongly decreased weld-heat-affected-zone toughness, particularly in the grain-coarsened region, that an increase in carbon moderately decreased toughness, and that an increase in manganese and nickel slightly decreased toughness.

The preceding observations were used extensively in selecting the carbon (0.10%), manganese (0.75%), sulfur (less than 0.010%), and nickel (5.0%) contents of the 5Ni-Cr-Mo-V steel that is considered extremely promising as an HY-130/150 steel.

Filler-Metal and Joining-Technique Development

Covered-Electrode Filler Metals.[6] To determine the feasibility of using the MIG-filler-metal compositions for covered-electrodes, a group of 14 compositions was selected and subsequently produced as AWS Class Exxx18 covered electrodes. The electrodes were used to deposit undiluted weld metals in the flat position with a 200 F preheat and interpass temperature. Radiographic inspection of the test weldments disclosed no unacceptable

weld-metal defects such as cracks or porosity. The compositions and mechanical properties of the experimental weld metals are shown in Tables III and IV, respectively. Thirteen of the 14 weld metals exhibited yield strengths in the range 130 to 140 ksi with Charpy V-notch shelf-energy absorptions in the range 50 to 62 ft-lb. An analysis of the effects of composition on weld-metal mechanical properties indicated the following:

1. Commercial-type covered electrodes can be used to deposit weld metals (containing normal levels of residual elements, such as 0.033% oxygen) that exhibit good toughness and a yield strength of 140 ksi.

2. Conventional, low-alloy weld metals containing as low as 0.05 percent carbon can exhibit yield strengths as high as 141 ksi.

3. Within the range of compositions studied, a minimum of about 2.0 percent manganese appears to be necessary to attain a yield strength of 140 ksi. The optimum combination of nickel and chromium appears to be about 2.0 and 1.0 percent, respectively.

MIG All-Position Procedures. To establish welding conditions that will enable operators to use the MIG welding process out of position with relatively short training periods, the following parameters were studied with the interrupted-arc MIG-welding process: (1) voltage, (2) current, (3) shielding gas, (4) wire diameter, (5) travel speed, and (6) gun angle. Results of this parametric study indicated that, of the shielding gases studied, a mixture of 80 percent argon and 20 percent carbon dioxide showed

the most promise. The desirable features of this gas mixture are (1) constant penetration over a workable range of voltage, (2) deep penetration, (3) good arc stability and bead shape, and (4) a linear increase in penetration with current. The helium-rich gas mixtures (such as 70% helium, 28% argon, 2% oxygen, and 70% helium, 26% argon, and 4% carbon dioxide) produced less penetration than the argon-carbon dioxide mixture and, in general, caused the penetration to be sensitive to voltage changes. Results also indicated that wire diameter and gun angle did not affect penetration and that the most significant effect on penetration was produced by current.

Weld-Metal Cooling-Rate Study.[7)] Although it was not part of the work being performed under Contract NObs-88540, the Air Reduction Company Research Laboratory recently completed a study of the effects of welding variables on weld-metal cooling rates. The study was conducted (1) to establish the basis for consistent reproduction of cooling rates by manipulation of welding variables, (2) to provide information that can be used to prepare specifications for controlling weld-metal properties, and (3) to determine actual cooling curves that can be used to determine the continuous-cooling transformation characteristics of promising weld-metal alloy systems. The results of the study indicated that the cooling rates are linearly related to travel speed and inversely related to the sum of the anode, cathode, and electrode-extension voltage drops. The arc-plasma

voltage drop, by itself, does not affect the cooling rate. An analysis of the results of this work provided equations relating welding conditions to cooling rate; thus, weld-metal cooling rates can be calculated if certain critical welding parameters are known.

Weldment Evaluation

Preliminary Explosion-Bulge Tests.[8] Previous production plates of an experimental 5Ni-Cr-Mo-V steel exhibited the strength, toughness, and weldability required for an HY-130/150 steel. Likewise, an inert-gas-shielded metal-arc (MIG) electrode developed by the Air Reduction Company, a covered electrode developed by the Arcos Corporation, and two covered electrodes developed by the McKay Company appeared promising as HY-130/150 filler metals. Four sets of 1-inch-thick weldments were fabricated by the indicated companies from the 5Ni-Cr-Mo-V steel with the four promising filler metals. The experimental HY-130/150 weldments were explosion tested (1 crack-starter and 2 bulge tests for each set) by the Naval Research Laboratory to obtain a preliminary assessment of the compatibility of the base metal with the various weld metals and to establish explosion-bulge performance levels for weldments having yield strengths in the range 130 to 150 ksi.

The results of the explosion-bulge tests showed that the base metal an the high-toughness MIG weldments underwent extensive plastic flow (3 explosive "shots") without fracture. For the lower-toughness

covered-electrode weldments, the three crack-starter weldments and three of the six bulge weldments fractured in 3 or less shots. All fractures initiated in the weld metal and propagated primarily in the weld metal. In several specimens the weld-metal cracks propagated as short tears in the base metal. Three of the six covered-electrode weldments withstood the 3 shots and exhibited extensive plastic flow without fracture. The weldments that did not fracture were reduced in thickness by about 6 percent, which was similar to the thickness reduction of the base-metal plate.

The explosion tests showed that experimental HY-130/150 weldments can be fabricated that will undergo extensive plastic flow during explosive loading without fracture. However, a tougher covered-electrode weld metal will be required to markedly reduce the probability of fracture during explosive straining. In addition, the development of HY-130/150 filler metals must be continued so that the best performance observed in the present tests on 1-inch-thick weldments, which were welded in the flat position with a 200 to 300 F preheat, can be obtained on heavier, more highly restrained submarine-hull weldments, which must be fabricated by out-of-position welding and preferably with a lower preheat.

Work in Progress

Base-Metal Weldability

The status of programs previously described in quarterly progress reports is as follows:

Development of Small-Scale Restraint-Cracking Test. To complete the correlation between the Laboratory cruciform specimen and the new small-scale specimen, the crack susceptibility of the 32 steels from the aforementioned statistical study[4,5] is being evaluated with the small-scale specimen. Test plates have been machined, and the specimens are being welded.

Manganese for Nickel Study. Steels that were evaluated in the corresponding base-metal study have been welded with an experimental HY-130/150 MIG filler metal, and specimens for mechanical-property evaluation are currently being machined.

Statistical Program on Heat-Affected-Zone Cracking. The program to estimate quantitatively the effects of chromium, molybdenum, and vanadium on the crack susceptibility of Ni-Cr-Mo-V steels is still in progress. The experimental steels have been melted, rolled, and heat-treated; restraint-cracking specimens have been welded and are currently being machined for subsequent inspection.

Evaluation of 5Ni-Cr-Mo-V Steel. The evaluation of 1/2-, 1-, and 2-inch-thick plates from the 80-ton electric-furnace heat of 5Ni-Cr-Mo-V steel is continuing. This evaluation includes (1) Laboratory cruciform restraint-cracking tests, (2) large-size restraint-cracking tests, (3) tension, bend, and impact tests of 2-inch-thick weldments, (4) gas-cut-bend tests, (5) impact tests of simulated weld-heat-affected-zone

microstructures, and (6) high-speed dilatometric measurements of simulated weld-heat-affected-zone microstructures.

Filler-Metal and Joining-Technique Development

MIG Major-Element Study. Nineteen of the previously described[1)] 34 experimental Mn-Ni-Cr-Mo filler metals have been drawn to welding wire and are currently being evaluated. The remaining 15 filler metals are being drawn to wire and should be available for evaluation in the next quarter.

Covered-Electrode Filler Metals. Based upon the results of the first covered-electrode filler-metal study, a second covered-electrode study has been initiated in which emphasis is being placed on determining the effects of composition on the properties of weld metals containing about 2.0 percent manganese, 2.0 percent nickel, and 0.50 percent molybdenum. This study should be completed by the end of the fourth quarter. In addition to the second covered-electrode composition study, a program has been undertaken to determine the effects of coating constituents on the toughness of covered-electrode weld metals. Specifically, the effects of the proportion and quality of gas-forming compounds and the effects of compounds affecting the slag-metal interaction are being investigated.

MIG All-Position Procedures. A parametric study of out-of-position interrupted-arc welding has been undertaken in which the results of the previous investigation will be checked by using manual welding procedures.

Weldment Evaluation

Explosion-Bulge Tests—Second Series. As will be described in the subsequent structural-evaluation discussion, a series of 1-inch-thick weldments fabricated from the 5Ni-Cr-Mo-V steel and the most promising MIG filler metal are being prepared so that the effects on explosion-bulge-test performance of undermatching and overmatching weld-metal yield strength can be determined.

Work Planned

No new joining-development studies are scheduled to begin during the next quarter. Emphasis will be placed on obtaining results from the evaluation of the 5Ni-Cr-Mo-V steel, the MIG major-element study, the covered-electrode developments, and the MIG all-position study.

STRUCTURAL EVALUATION

During the past quarter studies were completed on the relations between Charpy V-notch impact criteria and NDT values for experimental HY-130/150 steels. Evaluation of the 5Ni-Cr-Mo-V steel was started, and preliminary results have been obtained in the areas of fracture, formability, and fatigue.

Studies on the stretch forming of angles have been initiated. A forming questionnaire has been prepared for distribution by the Bureau of Ships to submarine fabrication yards. The results will assist in the planning of large-scale forming studies as well as provide information on current capabilities for forming an HY-130/150 steel.

Corrosion specimens of the 5Ni-Cr-Mo-V steel in both the welded and unwelded condition were exposed at Kure Beach to flowing sea water, nonflowing sea water, and marine atmosphere. In addition, similar corrosion specimens will be exposed to deep-ocean corrosion (2500 and 6000 feet) at Port Hueneme, California.

Work Completed

Drop-Weight Tear Tests of 5Ni-Cr-Mo-V Steel

Drop-weight tear tests of the 5Ni-Cr-Mo-V steel were conducted in the new 20,000 ft-lb capacity drop-weight machine. Both longitudinal and transverse 1-inch-thick specimens were prepared and tested in accordance with recommended NRL procedures with cast starter bars obtained from NRL. At 30 F the drop weight tear energies were 6000 and 5000 ft-lb for longitudinal and transverse specimens, respectively. Full-shear behavior was observed in all specimens. The results are shown in Figure 2, which was taken from a recent NRL report[9] and which shows the relationship between drop-weight tear energy and yield strength for several high-yield-strength steels. Note that even though the 5Ni-Cr-Mo-V steel was produced by conventional processing (air-melted, basic-electric-furnace, silicon-aluminum-deoxidized, air-cast), its drop-weight-tear energy absorption is equal to the highest value reported by NRL for "special-processing" steels.

Drop-Weight Tests of Experimental HY-130/150 Steels[10]

One of the most important requirements of HY-130/150 steels and weldments is high fracture toughness. For laboratory screening of experi-

mental steels, fracture toughness can be most conveniently determined from Charpy V-notch impact tests. However, fracture-toughness values obtained from drop-weight and explosion-bulge tests are also important, and correlations between these tests and the Charpy V-notch test have not been established for steels having yield strengths in the range 130 to 150 ksi. Therefore, Charpy V-notch and drop-weight tests were conducted on 1/2- and 1-inch-thick plates of four experimental HY-130/150 steels (3¾Ni-Cr-Mo-V, 5¼Ni-Cr-Mo-V, 5Ni-Cr-Mo-V, and 7½Ni-Cr-Mo steels) and HY-80 steel (heat-treated to a yield strength of 150 ksi) to determine the relation between Charpy V-notch and drop-weight test criteria and to determine the best method for obtaining fracture-toughness values to screen experimental HY-130/150 steels.

The results indicated that for HY-130/150 type steels, the drop-weight-test nil-ductility temperature (NDT) can be estimated from Charpy V-notch test data by determining the temperature corresponding to an energy absorption of about 40 ft-lb, a shear fracture of about 50 percent, or a lateral expansion of about 20 mils. The results also indicated that the explosion-bulge-test fracture-transition-plastic temperature (FTP), determined by adding 120 F to the NDT, is approximately the same as the 100 percent shear-fracture temperature in the Charpy V-notch test. Because the NDT and FTP temperatures estimated from the Charpy V-notch test values were significantly in error for several of the steels, additional study would be

required to establish a correlation that would be useful in service. However, for laboratory screening where the test material is limited, acceptable approximations of the NDT and FTP can be obtained from Charpy V-notch test data.

The NDT of 1-inch-thick specimens from the 5Ni-Cr-Mo-V production heat was -120 F.

Corrosion

Corrosion and stress-corrosion specimens of plates and weldments of the 5Ni-Cr-Mo-V production steel (as well as check specimens of a 5¼Ni-Cr-Mo-V production steel, a high-carbon Ni-Cr-Mo laboratory steel, and an HY-80 steel for comparison) were sent to Kure Beach for exposure to flowing sea water, nonflowing sea water, and marine atmosphere. The exposure times will be 1/2, 1, 2, and 4 years, or until cracking in the case of the stress-corrosion specimens.

Similar specimens of HY-80 steel were removed after a 6-month exposure and are currently being evaluated. Preliminary examination of the HY-80 specimens showed that the filler metal of welded specimens corroded somewhat in preference to the heat-affected zone and the base metal, as predicted from electrochemical-property tests described in the section on Work in Progress.

In addition, corrosion and stress-corrosion specimens (welded and unwelded) of the 5Ni-Cr-Mo-V steel were sent to the U. S. Naval Civil

Engineering Laboratory at Port Hueneme, California for exposure in deep-ocean corrosion tests (2500 feet and 6000 feet).

Work in Progress

Strength and Formability

Bend tests on seven promising steels, (including the 5Ni-Cr-Mo-V steel) having yield strengths in the range 92 to 169 ksi have been completed. The mechanical properties as measured in tension tests have been related to the bend angle at fracture, the ratio of thickness to final radius, the true strain at fracture, and the minimum bend radius in terms of plate thickness as measured in 3/8-inch-thick bend specimens.

The results show that all steels investigated as promising HY-130/150 steels have more than adequate ductility for forming to small radii, as determined by bend tests conducted under conditions of plane strain (width-to-thickness ratios of 8 or greater). As would be expected, steels with the highest percent reduction of area have the best formability. The relation between original thickness and outside radius at fracture in a bend test (h_o/r_o) and percent reduction of area in a tension test is shown in Figure 3. Similar relations have been developed between other bend-test criteria and tensile properties. A report on this work will be issued during the next quarter.

Prior to actual shipyard forming to determine the effects of cold forming on the mechanical properties of 2-inch-thick plates of the

5Ni-Cr-Mo-V steel, information on current forming requirements and capabilities is required. Thus, a forming questionnaire has been prepared and forwarded to the Bureau of Ships for distribution to various submarine fabrication yards.

Information to be obtained from the questionnaire includes the plate-forming capacities of existing equipment for different steels, a summary of the plate-forming limits used in current submarine-hull construction, forming ranges for hull stiffeners, and an estimate of the current capabilities for cold forming HY-130/150 steels.

Preliminary arrangements have been made to investigate the stretch forming of HY-80 steel, 5Ni-Cr-Mo-V steel, and a 12Ni-5Cr-3Mo steel. The Ling-Temco-Vought Corporation of Dallas has a 100-ton stretch-forming machine capable of stretch forming 2- by 2- by 3/8-inch angles. This shape was chosen to simulate T-sections currently used in submarine-hull construction and still be within available machine capacities.

Fracture

Explosion-bulge specimens of the 5Ni-Cr-Mo-V steel at several strength levels are being prepared to study the effects of over-, under- and equal-matching filler metals. A 10 per inch photogrid will be placed on the outer surface to analyze the strain distribution throughout the weldment, and procedures similar to those used by Hartbower and Pellini[11)] on A201 Grade A steel will be used.

Preliminary results of the drop-weight bulge test appear quite promising. This test is being developed so that the fracture toughness of weldments can be evaluated in the laboratory under biaxial loading. Thus, different welding procedures can be evaluated without resorting to the more expensive explosion-bulge tests.

A 14- by 14- by 1/2-inch plate is placed over a 9-inch-diameter die and impacted by a hemispherical mandrel having a 7-inch diameter. When the 5Ni-Cr-Mo-V steel was subjected to repeated blows of about 20,000 ft-lb, a uniform bulge (no cracking) having a maximum percent reduction in thickness of 26 percent was measured. A section through the bulge is shown in Figure 4. Strain analysis and preliminary tests of weldments and other steels are currently in progress.

Fatigue

The hydraulically operated low-cycle fatigue machines are now in operation and the dynamic-strain measuring systems are being calibrated. Preliminary tests on HY-80 steel and the 5Ni-Cr-Mo-V steel are in progress.

Because of the large volume of weld metal that must be removed from the currently used welded fatigue cantilever beam specimens, these specimens may not satisfactorily simulate the fatigue of actual weldments. Thus a full thickness (½-inch-thick) butt-welded fatigue specimen is being developed. Preliminary results indicate that by tapering the width of the specimen, a 3-inch-long region of constant strain can be obtained. Thus,

a transverse full-thickness weld (with only the reinforcement ground off) can be fatigue tested under constant-strain conditions.

Testing of 5Ni-Cr-Mo-V steel rotating-beam fatigue specimens at 10 cycles per minute has been completed, and the results are currently being analyzed. Average results of the four conditions studied—smooth-surface specimens tested in air and synthetic sea water, and notched-surface specimens tested in air and synthetic sea water—are shown in Figure 5 for the 5Ni-Cr-Mo-V steel as compared with HY-80 steel for all testing conditions.

Corrosion

Electrochemical studies of HY-80 steel, 5¼Ni steel, and 5Ni-Cr-Mo-V steel are being conducted in synthetic sea water to determine the corrosion resistance of welded steels in sea water. The open-circuit potential and cathodic-polarization characteristics of the filler metal, heat-affected zone, and base metal are being determined. In addition, galvanic studies are being conducted with specimens of filler metal and base metal. The results of these studies show that the weld metal is anodic to the base metal. The measurements are consistent with the qualitative observation on HY-80 specimens after a 6-month exposure to marine environments, which showed that the filler metal corrodes in preference to the base metal of welded specimens. A study is being planned to

determine whether hydrogen absorption (from cathodic protection) will embrittle welded HY-80 steel and to establish a benchmark for HY-130/150 steels.

Work Planned

The programs now in progress will be continued during the next quarter.

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Table I

Longitudinal Yield Strength and Energy Absorption of 5Ni-Cr-Mo-V Steels with Various Carbon Contents

Steel	Carbon Content, %	Yield Strength (0.2% Offset), ksi				Charpy V-Notch Energy Absorption at 0 F, ft-lb			
		Water-Quenched		Blower-Cooled		Water-Quenched		Blower-Cooled	
		1000 F	1100 F	1000 F	1100 F	1000 F	1100 F	1000 F	1100 F
A	0.05	135	137	104	110	126	125	115	151
B	0.10	147	145	135	140	86	100	96	111
C	0.16	152	152	154	152	78	81	70	80
D	0.22	156	156	163	157	62	75	55	67
E	0.26	163	162	166	158	51	57	45	56

NOTE: Plate samples (½-inch-thick) were austenitized at 1500 F for 30 minutes, water-quenched, tempered at the indicated temperature for 30 minutes, and water-quenched; or they were austenitized at 1500 F for 2 hours, blower-cooled, tempered at the indicated temperature for 2 hours, and blower-cooled.

Table II

Chemical Composition of Steels Used To Study Effect of Minor Elements and Minor Variations in Major Elements—Percent

Steel	Distinguishing Features	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al*	N**
	0.10 Percent Carbon Steels											
A	Base Steel	0.09	0.74	0.008	0.007	0.25	5.17	0.55	0.55	0.070	0.021	0.005
B	High Mn, Low Si	0.11	0.88	0.012	0.007	0.04	5.09	0.56	0.56	0.075	0.025	0.005
C	Low Cr, High Mo	0.09	0.79	0.011	0.010	0.26	5.17	0.02	0.79	0.070	0.027	0.004
D	Low Mo, High Cr	0.10	0.80	0.003	0.004	0.26	4.95	1.26	<0.01	0.065	0.025	0.005
E	Low Al	0.09	0.73	0.005	0.006	0.25	5.10	0.56	0.57	0.068	0.006	0.009
	0.15 Percent Carbon Steels											
F	Base Steel	0.16	0.74	0.005	0.003	0.25	4.90	0.57	0.55	0.074	0.021	0.006
G	Low Al	0.15	0.72	0.006	0.003	0.24	4.90	0.57	0.55	0.072	0.005	0.004
H	Low Mn, Low Si, High Cr, High Mo	0.16	0.14	0.006	0.007	0.03	5.10	1.49	0.89	0.075	0.030	0.005

*Acid soluble.
**Kjeldahl determination.

(40.018-001)(24)

Table III

Compositions of Experimental HY-130/150 Covered-Electrode Weld Metals—Percent

Variable	Electrode Number	C	Mn	P	S	Si	Ni	Cr	Mo	Ti	Al*	N	O
Nickel	Z735	0.060	2.00	0.012	0.015	0.44	1.74	1.00	0.54	0.018	0.008	0.010	0.032
	Z737	0.050	1.98	0.010	0.015	0.41	2.08	0.98	0.52	0.018	0.009	0.009	0.036
	Z738	0.050	2.01	0.072	0.016	0.40	2.45	0.98	0.54	0.018	0.007	0.010	0.032
Chromium, low Manganese	Z747	0.066	1.81	0.008	0.016	0.42	1.74	0.90	0.54	0.020	0.008	0.009	0.032
	Z748	0.067	1.83	0.008	0.015	0.42	1.76	1.21	0.61	0.014	0.008	0.009	0.032
	Z749	0.066	1.81	0.008	0.016	0.41	1.74	1.51	0.56	0.020	0.008	0.009	0.030
Chromium, medium Manganese	Z735	0.060	2.00	0.012	0.015	0.44	1.74	1.00	0.54	0.018	0.008	0.010	0.032
	Z741	0.050	1.97	0.011	0.014	0.43	1.74	1.25	0.53	0.018	0.009	0.010	0.032
	Z742	0.045	2.00	0.011	0.013	0.41	1.80	1.54	0.54	0.016	0.007	0.010	0.034
Chromium, high Manganese	Z743	0.044	2.20	0.011	0.013	0.43	1.78	1.01	0.54	0.017	0.007	0.010	0.031
	Z744	0.045	2.21	0.010	0.013	0.43	1.79	1.26	0.54	0.017	0.008	0.010	0.034
	Z746	0.070	2.28	0.007	0.015	0.45	1.76	1.37	0.54	0.020	0.008	0.011	0.031
	Z745	0.068	2.29	0.007	0.015	0.43	1.75	1.52	0.58	0.019	0.008	0.009	0.033
Low Silicon	Z739	0.058	1.86	0.011	0.017	0.27	1.73	0.99	0.53	0.015	0.008	0.010	0.033
High Molybdenum	Z740	0.050	2.00	0.009	0.014	0.44	1.74	0.99	0.73	0.018	0.009	0.009	0.034

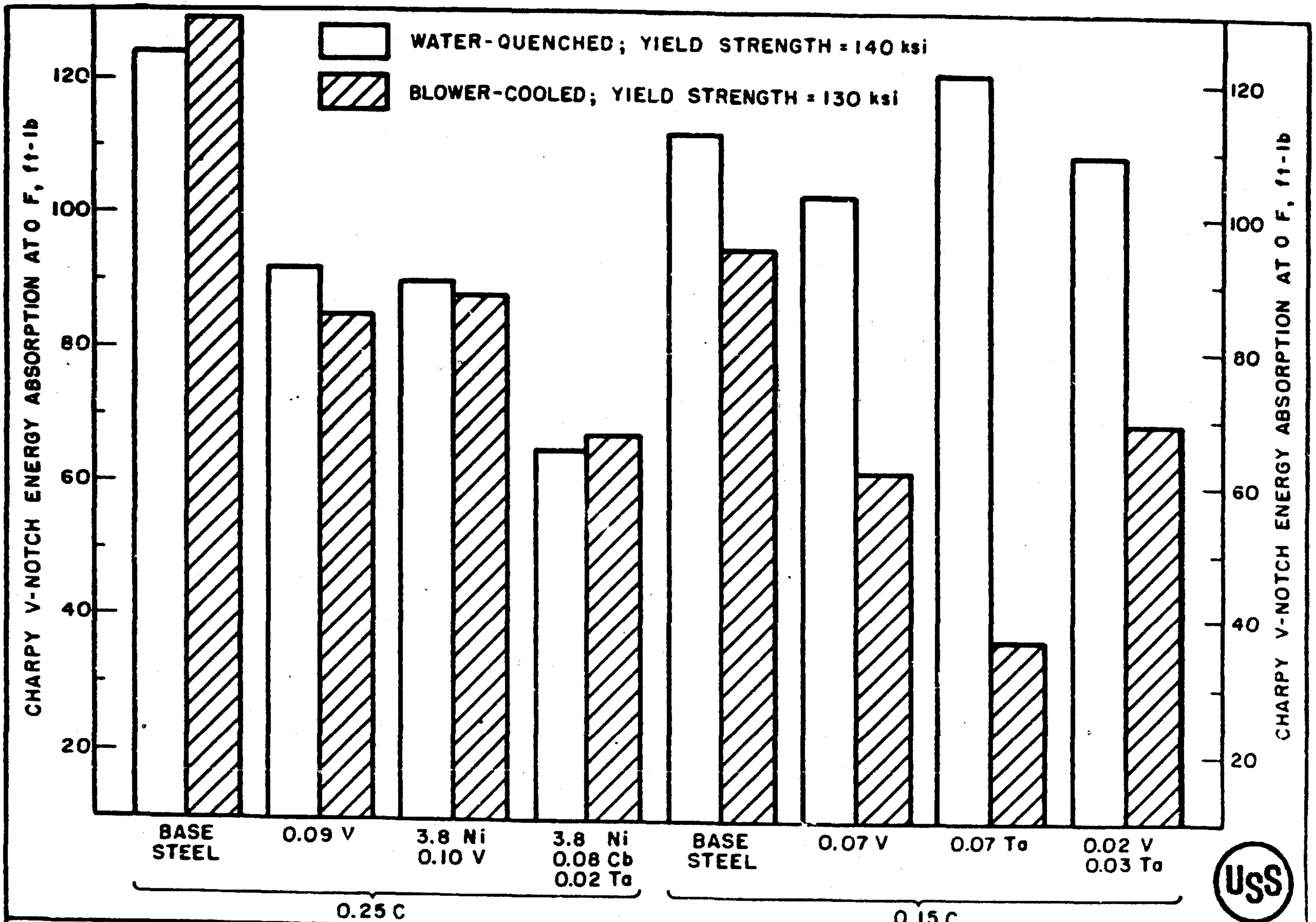
*Acid soluble.

Table IV

Mechanical Properties of Experimental HY-130/150 Covered-Electrode Weld Metals

Variable	Electrode Number	0.505 Tension-Test Results* Yield Strength (0.2% Offset), ksi	Tensile Strength ksi	Elongation in 2 inches %	Reduction of Area, %	Charpy V-Notch Impact-Test Results* Energy Absorption, ft-lb +80 F	Energy Absorption, ft-lb -60 F	20 ft-lb Transition-Temperature, F
Nickel	Z735	138	144	17.8	52	57	38	-115
	Z737	140	145	18.0	50	61	43	-145
	Z738	141	150	15.5	40	59	41	-150
Chromium, Low Manganese	Z747	131	139	21.0	63	62	39	-144
	Z748	135	143	17.5	46	58	38	-136
	Z749	133	145	17.0	47	62	42	-145
Chromium, medium Manganese	Z735	138	144	17.8	52	57	38	-115
	Z741	134	147	17.0	43	58	34	-130
	Z742	141	153	15.3	35	55	35	-110
Chromium, high Manganese	Z743	134	145	18.5	56	61	34	-145
	Z744	139	149	17.3	47	52	31	-130
	Z746	137	148	9.3	21	52	27	-120
	Z745	140	155	12.0	28	50	28	-120
Low Silicon	Z739	126	133	18.8	55	62	44	-150
High Molybdenum	Z740	140	144	15.3	33	61	33	-145

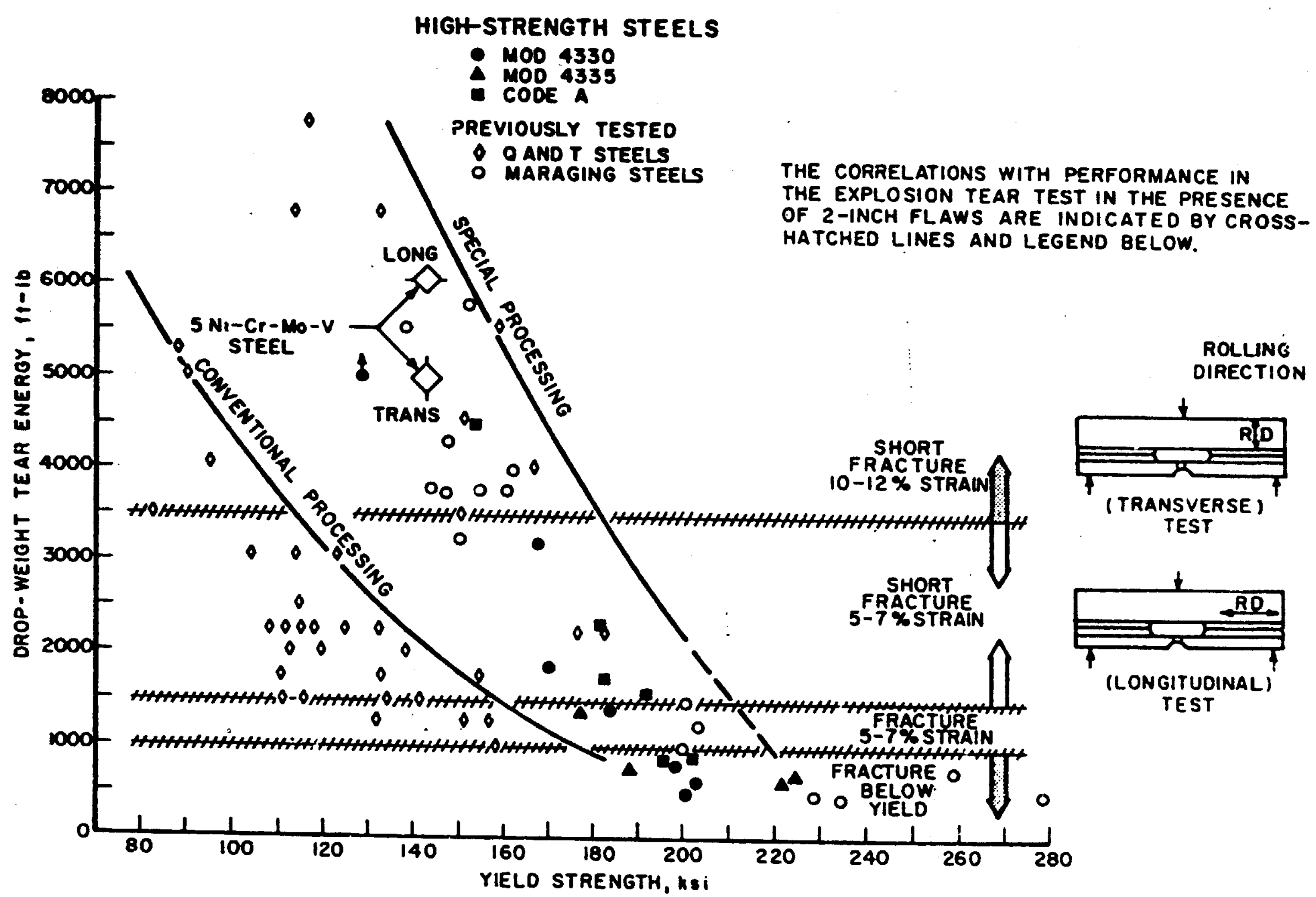
* Results are the average of two or more tests.



EFFECT OF COMPOSITION ON THE ENERGY ABSORPTION OF 1/2-INCH-THICK PLATES OF THE 3Ni-1.5Cr-0.9Mo STEELS

DRAWN BY	CHK'D BY	APPROVED BY	UNITED STATES STEEL CORPORATION	FIGURE NO.
A. J. C.	S. J. M.	J. H. G.	APPLIED RESEARCH	1
DRAWING NO. ARL 18-300		PROJECT NO. 40.018-001 (24)	PITTSBURGH, PA.	
		DATE 1/3/64		

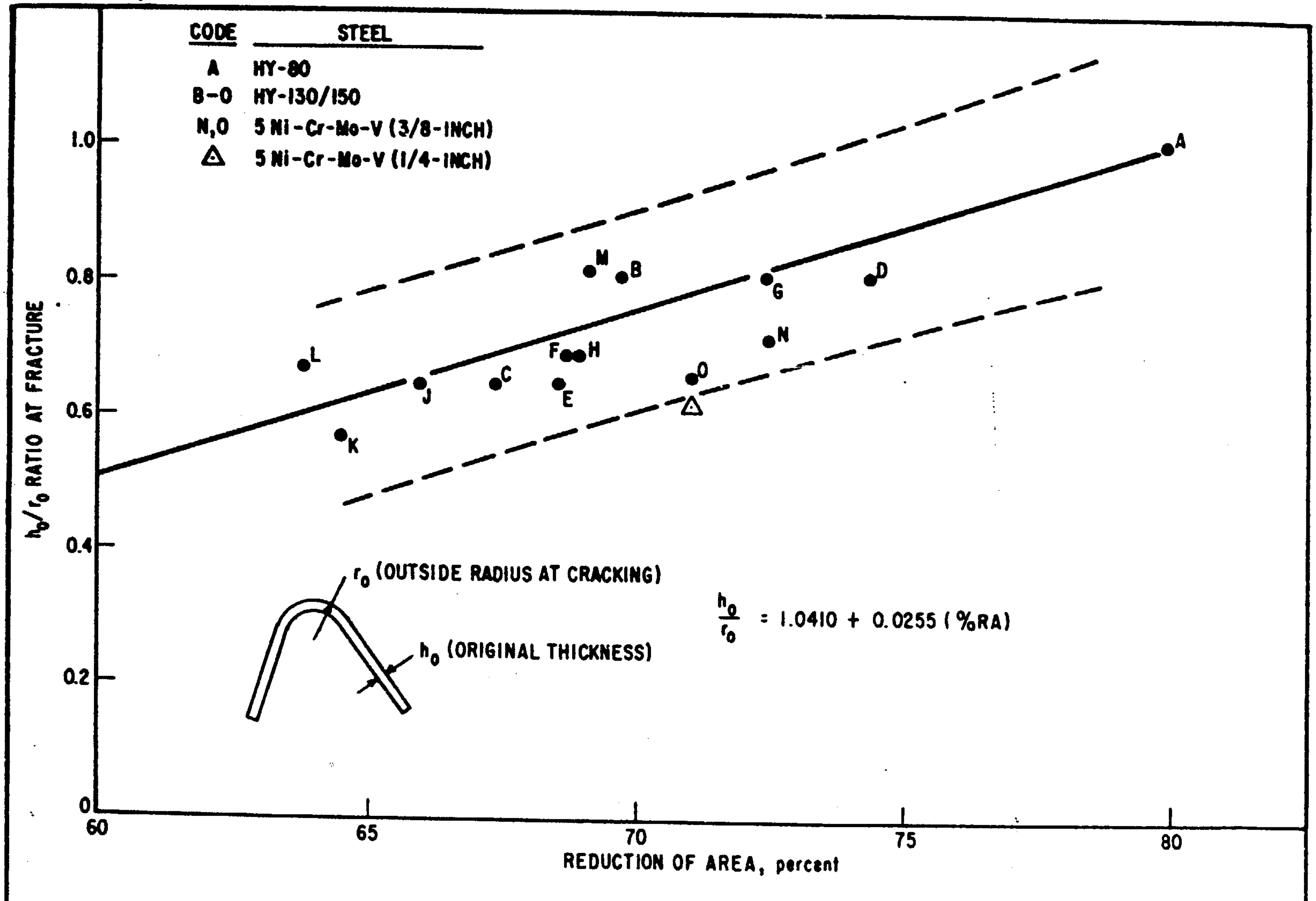
1025 Clearprint Pitt Photo Litho Co., Inc. Pgh., Pa.



SUMMARY OF DROP-WEIGHT TEAR AND YIELD-STRENGTH RELATIONSHIPS FOR STEELS (FROM REFERENCE 9)

DRAWN BY	CHK'D BY	APPROVED BY		
G.A.Z.	L.F.P.	L.F.P.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 2
DRAWING No		PROJECT No 40.018-001(24)		
ARL 18-351		DATE 4-8-64		

36-18242 REV. 1063



RELATION OF h_0/r_0 RATIO AT FRACTURE IN BEND TESTS TO PERCENT REDUCTION IN AREA FROM TENSION TESTS FOR PROMISING HY-130/150 STEELS

DRAWN BY M.M.	CHK'D BY L.F.P.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 3
DRAWING No ARL 18-352		PROJECT No 40.018-001 (24) DATE 4/8/64		

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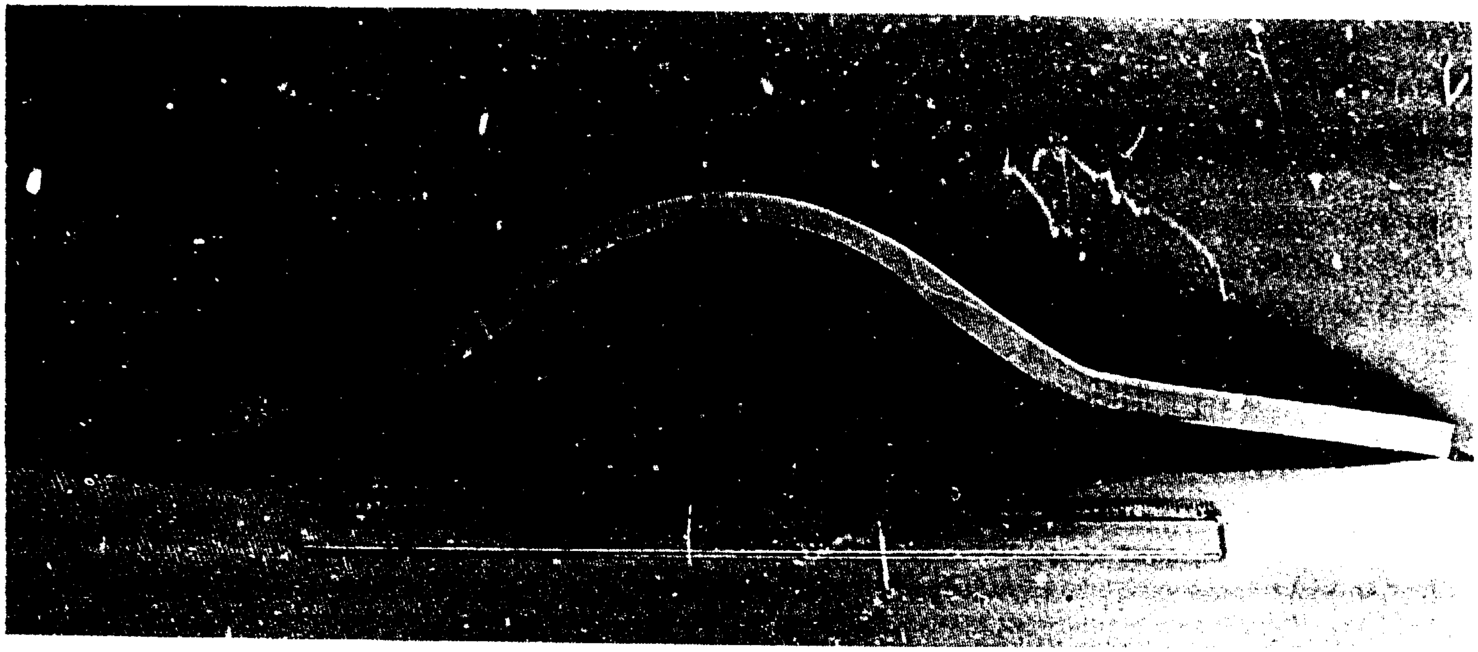

Figure 4. Drop-weight bulge test of 1/2-inch-thick plate of 5Ni-Cr-Mo-V steel.

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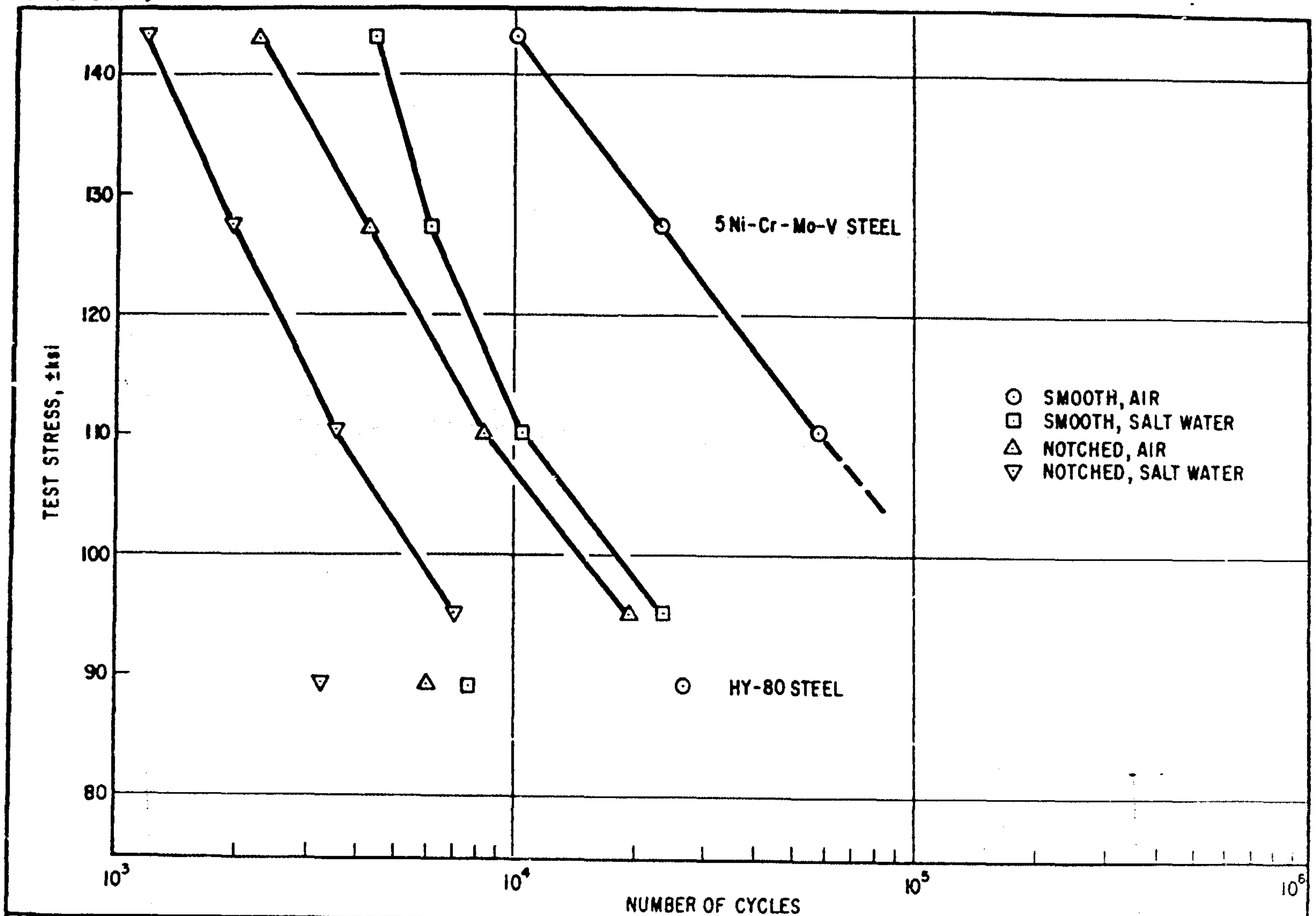

FATIGUE RESULTS FOR SMOOTH- AND NOTCHED-SURFACE SPECIMENS OF STEELS TESTED AT 10 CYCLES PER MINUTE IN AIR OR SALT WATER

DRAWN BY M.M.	CHK'D BY L.F.P.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION	FIGURE NO.
DRAWING No.		PROJECT No. 40.018-001 (24)	APPLIED RESEARCH	5
ARL 18-354		DATE 4/8/64	PITTSBURGH, PA.	

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